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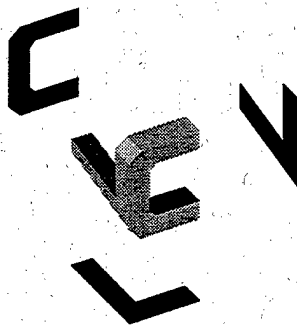
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**FROM IMAGE ANALYSIS TO COMPUTER VISION:
MOTIVES, METHODS, AND MILESTONES**

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ABSTRACT

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ABSTRACT

Almost as soon as digital computers became available, it was realized that they could be used to process and extract information from digitized images. Initially, work on digital *image analysis* dealt with specific classes of images such as text, photomicrographs, nuclear particle tracks, and aerial photographs; but by the 1960's, general algorithms and paradigms for image analysis began to be formulated. When the artificial intelligence community began to work on robot vision, these paradigms were extended to include recovery of three-dimensional information, at first from single images of a scene, but eventually from image sequences obtained by a moving camera; at this stage, image analysis had become *scene analysis* or *computer vision*. This paper reviews research on digital image and scene analysis through the 1970's. This research has led to the formulation of many elegant mathematical models and algorithms; but practical progress has largely been due to enormous increases in computer power, allowing even "brute force" algorithms to be implemented very rapidly.

Keywords: Image processing, Image analysis, Pattern recognition, Scene analysis, Computer vision

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July 24, 1998

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Enclosed please find two copies of a technical report which reflects work performed on Grant N00014-95-1-0521.

Sincerely,

A handwritten signature in cursive script that reads "Kathy Bumpass".

Kathy Bumpass
Information Technology Support
Assistant

Enclosure: Azriel Rosenfeld, "From Image Analysis to Computer Vision: Motives, Methods, and Milestones", CAR-TR-892, CS-TR-3920, July 1998

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1 Computers and images

In the 1950's, digital computers began to become available in research laboratories and to be used for processing various types of data. By the mid '50s, it was realized that computers could be used to process images, if the images could first be converted to digital form. An image is digitized by *sampling* its lightness value ("gray level") at a regularly spaced array of points and *quantizing* it into a discrete set of values. [We are assuming that the image is "black-and-white"; no attempt was made to deal with color images in those days.] The resulting array of numbers, representing the gray levels of individual picture elements ("pixels"), can, if necessary, be input to the computer using punched cards or tape [45, 233, 234]; but it is much less tedious if some direct means of inputting image data to the computer can be provided. This can be done by *scanning* the image, using a drum scanner [141] or flying spot scanner [92], to yield a time-varying signal; this signal can then be sampled, quantized, and input to the computer directly.

Once an image has been input to a computer, the computer can be programmed to do a great variety of things to it. As we shall see in Section 2, an image can be *processed* to produce other images, or it can be *analyzed* to derive various types of descriptive information about it—for example, to classify it in some way ("pattern recognition"). [Conversely, descriptive information can be used to *synthesize* images; image synthesis later became a major area of *computer graphics*. The conceptual relationship among image processing, image analysis, and image synthesis is summarized in the 2-by-2 table shown in Figure 1.] Note that image processing requires not only a method of inputting images to the computer, but also a method of outputting or *displaying* the processed images. Today's high-resolution computer-driven displays were still far in the future, but there were simple ways to generate hard-copy images, including the use of overstrike to create halftone-like "grayscale" images on an alphanumeric printer. An example of an image displayed in this way is shown in Figure 2; a paper on optimization of overstrike-based grayscales is [110].

Digital computers were by no means the only tools that could be used to process or analyze images. Many early systems used analog circuits to process image-derived signals, or used optical imaging for parallel processing of images represented in the form of transparencies. But the ability of general-purpose computers to perform arbitrary operations on digitized images insured that digital methods would continue to be used; and the steadily increasing speed of digital computers is rapidly overcoming the speed advantages of competing implementations.

This paper reviews research on digital image and scene analysis through the 1970's. Sections 2–3 describe some of the main areas of application of image analysis and discuss why image analysis, unlike image processing, required the development of new concepts and techniques. Section 4 summarizes early work on basic image analysis techniques, including segmentation, property measurement, and structural description. Section 5 explains why more powerful techniques were needed to describe images of three-dimensional scenes. Section 6 lists milestone conferences, books, and journals dealing with the field as a whole or with specific application areas.

2 Processing and analysis

Initially, image processing had an important advantage over image analysis: There already existed a well-developed theory of signal processing that generalized more or less straightforwardly to two-dimensional signals (i.e., to images), and that applied to digital as well as analog signals. The increasing importance of television and facsimile led to a growing interest in image communication, with particular emphasis on image bandwidth compression or *coding*. Advances in image reproduction (photography, xerography, etc.) and display led to the development of methods of measuring image *quality* and to research on image *enhancement* (quality improvement by contrast stretching, deblurring, noise reduction, etc.) and *restoration* (estimation and correction of image degradations); such techniques could also be used for “preprocessing” images as a preliminary to describing or classifying them. A more recent branch of image processing is the *reconstruction* of cross-section images from projections, as in computed x-ray tomography.

For image analysis, on the other hand, there was little or no preexisting theory. Basic signal analysis techniques such as Fourier analysis or matched filtering can be applied to images; but practical image analysis applications, such as those described in Section 3, almost always require more powerful techniques. (The patterns of interest for describing images are usually not sinusoids, and often cannot be detected by exact matching.) Thus progress on these applications was accompanied by the invention of many of today’s basic methods of image analysis, as described in Section 4.

3 Motives: Image analysis applications

General theories of image analysis were slow to emerge because image analysis systems were developed to deal with specific classes of images and to derive domain-specific descriptions of these images. Some of the major areas of application of image analysis are briefly discussed in the following paragraphs; references to early work on these areas will be given in Section 6.

- a) *Character recognition*. Computers deal extensively with alphanumeric information which is conventionally input by hand using a keyboard. This information often already exists in human-readable hard-copy form; if the computer could reliably recognize the characters (letters, numbers, etc.) in a digitized image of the hard copy, keyboard input could be eliminated. Thus some of the earliest work on image analysis was aimed at developing effective methods of character recognition. [The task was called *optical character recognition* (OCR) not because it was implemented optically, but to distinguish it from *magnetic ink character recognition* (MICR), in which the characters were printed in magnetic ink to make them easily detectable, and were given special shapes to make them easily recognizable.] Character recognition problems vary widely in difficulty; cleanly machine-printed characters, especially if they are in a known font, are relatively easy to recognize, but hand-printed characters still pose problems, and the recognition of cursive script is still an active research area.
- b) *Microscopy*. Optical and electron microscope images are used for many purposes in such fields as materials science, biology, and medicine. The medical applications, in

particular, involve the routine examination of hundreds of millions of images a year by pathologists, hematologists, and geneticists, for such purposes as chromosome mapping, blood cell counting, and pap smear analysis. Not surprisingly, attempts to automate some of these tasks began as early as the 1950's, and work in this area is still ongoing.

- c) *Radiology.* The development of three-dimensional medical imaging techniques (computed tomography, magnetic resonance imaging, and so on) over the past few decades is a major accomplishment of computer image processing, and provides important new sources of images for analysis. Long before such images became available, hundreds of millions of conventional x-ray images a year were being examined by radiologists (as well as by dentists, engineers, and many others); but relatively little work seems to have been done prior to the 1970's on the automation of radiographic image analysis. The analysis of both conventional radiographs and three-dimensional medical images continues to be an active area of research.
- d) *Remote sensing.* Images are the primary source of information about distant objects; thus image analysis plays a central role in astronomy. For over a century, aerial images of the earth's surface have provided "bird's-eye views" from which valuable information can be derived about agriculture, natural resources, hydrology, geology, geography, and cartography, and for use in military reconnaissance or environmental monitoring. As early as the 1950's, research had begun on the automatic recognition of cultural features (buildings, roads, bridges, ...) in aerial photographs. Since the 1960's, larger-scale views of the earth and the atmosphere have been provided by satellite images. Huge numbers of such images have been acquired, but only a small fraction of them have been examined in any detail; thus there is a continuing need to develop automatic techniques for extracting and analyzing the information that these images contain.
- e) *Other areas.* Images are collected and examined in many other areas of science and engineering; thus computer image analysis has many other potential areas of application. An example of such an area is forensic science; a classical task in this area is the recognition of fingerprints, and a more difficult task is face recognition. Another area, in which there was considerable activity a few decades ago, is high energy physics. The study of subatomic particles was greatly advanced, around the middle of this century, by the development of devices such as the cloud chamber and the bubble chamber, in which the particles left visible "tracks". The search for new particles, and the measurement of their properties, involved the analysis of thousands of images, with the goal of detecting the tracks of rare particles, measuring their geometric properties, and detecting "events" (abrupt changes) representing particle interactions.

The types of images that need to be analyzed in these widely varying domains are very different, but the types of analyses that need to be performed on these images have many things in common. Image analysis almost always involves a few basic processes: distinguishing certain parts of the image (representing characters, blood cells, tumors, wheat fields, particle tracks, fingerprint ridges, facial features, ...); measuring properties of these parts, or relations among the parts; and using the values of these properties or relations to classify or describe the parts, or to describe or classify the image as a configuration of parts.

These processes define the general image analysis/recognition paradigm shown in Figure 3. In Section 4 we will describe some of the methods that were developed to implement these processes.

4 Methods: Image analysis algorithms

4.1 Segmentation

As pointed out in the last paragraph, the images that we are usually interested in analyzing contain parts that represent visibly different entities, and the desired descriptions of the images involve these parts. Thus *segmentation* of an image into “meaningful” parts is almost always the first step in any image analysis process.

In some simple situations, the entities differ in lightness; thus the pixels belonging to image parts that represent different entities have different ranges of gray levels. If these ranges are more or less disjoint, the image can be segmented into parts by *thresholding* the pixel gray levels—i.e., comparing the gray levels to some reference value(s), and assigning them to classes depending on which range they lie in. The character recognition domain is perhaps the most obvious example of this situation: characters are usually much darker than the paper on which they are printed or written. Thresholding can also provide meaningful segmentations for more complex types of images; for example, in (suitably stained) microscope images of cells, the nuclei of the cells are generally darker than the cell bodies, which in turn are darker than the background. The suitability of thresholding for segmenting an image can be determined by examining the population of pixel gray levels in the image; this can be done by constructing a bar graph (a *histogram*) in which each bar corresponds to a gray level, and its height indicates the number of pixels having that gray level. Peaks in this histogram, separated by valleys, represent subpopulations of pixels that have distinctive ranges of gray levels; evidently, a threshold corresponding to the bottom of a valley between two peaks will well separate the subpopulations corresponding to the peaks [201]. For a survey of thresholding methods see [261]. More general methods of segmentation by peak (i.e., cluster) detection in color space or local property value space are described in [188, 40].

If the gray level ranges of the image parts overlap, or vary from place to place in the image because of “shading” (due, for example, to slowly varying illumination), global thresholding becomes relatively useless as a method of segmentation, though local thresholding can still be used if the gray levels of neighboring parts are disjoint [33]. More generally, image parts are often distinguishable because there are abrupt jumps in gray level at their boundaries. Such jumps (*edges*) can be detected by examining the image gray levels in the neighborhood of each pixel and checking for large differences. The highest directional rate of change of a function f in the neighborhood of a point is called the *gradient* of f ; the usefulness of the gradient for edge detection was pointed out as early as the 1950’s [147]. (The same paper discussed the Laplacian and its use for approximate inversion of diffusion blur.) The magnitude and direction of the gradient of f can be computed from the values of the partial derivatives of f in two directions; in digital images, analogously, one can use first differences instead of derivatives. An early example, using differences between adjacent pixels in the two diagonal directions, can be found in [206]. An important early discussion of edge detection,

which unfortunately appeared only in report form, is [113]; it discusses linear and nonlinear operations for the detection of both “step” and “roof” edges. A surface fitting approach to gradient estimation is described in [200]. Other early approaches to step edge detection can be found in [124] (using best-fitting step functions) and [229] (using differences of average gray levels in neighborhoods of many sizes, and selecting a “best” size at each point). (In [139], edge detection applied to a reduced-resolution image is used to guide the search for edges in a full-resolution image.) For a statistical treatment of edge detection see [91]; on evaluation of edge detection algorithms see [1]; and for a survey of edge detection techniques see [42].

Edges are the most common locally detectable image features; other types are spots, curve ends, curves (including straight lines), and corners. The conventional way of detecting such features is to use higher-order difference operators, but such operators are not pattern-specific; for example, the second difference in the x direction may be higher for a high-contrast vertical edge than it is for a low-contrast vertical line. A better approach [229] is to use operators that incorporate logical conditions—for example, a bright vertical line is present in the neighborhood of pixel P only if P has a higher gray level than both its horizontal neighbors, and the same is true for both of P ’s vertical neighbors. Methods of feature detection using basis functions are described in [125, 68, 127]; a general class of local operators is defined in [84]. (The “morphological” operations that became popular in later years originated quite early; on the two-valued case see [141] and [174], and on the grayscale case see [180].) On digital arcs and curves see [213]; on digital straight lines see [215].

Local operators can detect features in the neighborhoods of individual pixels, but cannot link the local detections that correspond to an entire curve or an entire region boundary. Such global features can be extracted by a search process that finds sets of feature pixels that are optimal with respect to, e.g., both gray level contrast and geometric smoothness [173, 163, 164]. If a global feature has a simple geometric shape—for example, if it is straight—it can be converted to a local feature (a “spot” or cluster) by mapping the image into a suitably defined parameter space; for example, collinear feature points all map into the same point in a line parameter space [121, 47].

Image parts of known shapes can also be detected by “template matching”. Matching methods are also studied in image processing; but many such methods, particularly those involving inexact matching, were developed in an image analysis context [7, 10, 59, 6, 14, 256, 230, 273, 274, 202].

An image can also be segmented into *connected components*: maximal regions in which neighboring pixels have (almost) the same gray level [176], or more generally, into regions that are good fits to simple functions [191]; pairs of adjacent regions can then be merged if they are not separated by strong edges or their union is still simple, or more generally, if merging them results in a “better” partition of the image [22, 55, 93, 276, 119, 247, 120, 30]. For a survey of region-based segmentation techniques see [280].

Multiscale methods of image processing and analysis, as used in feature detection, segmentation, matching, etc., are conveniently implemented if a multiscale (“pyramid”) image representation is used [246]. On the related idea of variable-scale (“quadtree”) image representation see [142].

Methods of feature detection and segmentation are reviewed in [210], Ch. 8 and in [208,

152, 200, 205, 101, 223]. (It should be pointed out that in pattern recognition, any property of a pattern that is used for classification purposes is called a “feature”; but in image analysis, the term “feature” refers to a locally detectable pattern in an image.) On interpretation-guided segmentation see [248]; on convergent evidence in segmentation see [169]. Iterative methods of image segmentation, or more generally of labelling image parts, are discussed in [224, 218].

4.2 Properties

A wide variety of properties of an image or of its parts can be defined. The lightness (or darkness) and “contrastiness” of an image are described by the mean and standard deviation of the pixel gray levels in the image; these statistics can be computed from the image’s histogram. An image can be *normalized* with respect to linear transformations of its grayscale by shifting and scaling its gray levels so as to standardize the values of their mean and standard deviation.

Textural properties of an image can be described using statistics of higher-order gray level distributions of its pixels; for example, for any given spatial displacement δ , a second-order distribution is defined by the numbers of pairs of pixels at separation δ that have given pairs of gray levels [131, 104]. Alternatively, textural properties can be described using first-order statistics of the values of local properties measured at every point of the image [207]; second-order statistics of local property values can also be used [43]. Still another approach is to segment the image into microregions (“texels”) and use statistics of properties of these regions [156]. Reviews of methods of texture analysis can be found in [109, 103]. On the statistical analysis of spatial data see [15], and on fractal models see [157]. An early meeting on texture analysis was [300], and a workshop on (statistical) image modeling was [222].

Any *linear* property of an image is a weighted sum of its pixel values ([210], Ch. 7). *Moments* are an important class of linear properties in which the weights are monomials of the form $x^i y^j$ [122, 123, 80, 5]. An image can be *normalized* with respect to translation, rotation, and scale by shifting, rotating, and rescaling it so as to standardize the values of its first- and second-order moments ($1 \leq i + j \leq 2$). But many important image properties cannot be expressed as linear combinations of local properties [172].

Image parts can also be described by a wide variety of *geometric* properties, and can be decomposed into subparts based on geometric criteria. For example, an image part can be decomposed into its *connected components* (maximal connected subsets) [211, 216]. A connected image part S whose complement \bar{S} is also connected is called *simply connected*; if \bar{S} is not connected, the components of \bar{S} that are surrounded by S are called *holes* in S .

The set of pixels of S that have neighbors in a given component of \bar{S} is called a *border* B of S . Starting at any pixel P of a border B , an algorithm can be defined [227] that successively visits all the pixels of B and returns to P . The succession of moves from neighbor to neighbor made by this algorithm define the *chain code* of B [62, 64, 65, 66]. The smoothed direction of the border defines its *slope*, and the rate of change of this direction defines its *curvature*. A border can be decomposed into a succession of convex and concave parts in which its curvature is positive or negative [63]. The shapes of borders (i.e., of closed curves) can be analyzed in many ways; for examples see [12, 203, 279, 225, 195]. (Fourier analysis of the

shape of a border seems to have been first used in 1950's reports by Joseph on the AN/GSQ-14 Electrophotographic Viewer.) A book on shape description is [21]; a survey of shape analysis algorithms is [193].

Another algorithm can be defined that computes the intrinsic *distance* [228], i.e. the shortest number of moves within S , from each pixel of S to the nearest pixel of \bar{S} ; the result of this computation is called the *distance transform* of S [227]. The set of local maxima of the distance transform is called the *medial axis* of S [19, 175]. A connected S is called *elongated* if its area is much greater than the maximum value of its distance transform. Elongated parts of S can be extracted by *shrinking* S (deleting pixels with low distance values) and then *reexpanding* it (i.e., shrinking its complement) by the same amount; the resulting S' must be a subset of S , and sufficiently large connected components of $S - S'$ must be elongated parts of S (which can be of arbitrary *thickness*, depending on how much shrinking and reexpanding is needed to detect them). Similarly, expanding and reshinking S gives a superset S'' of S , and large connected components of $S'' - S$ must have arisen from clusters of parts of S [174, 210]. Algorithms can be defined for *thinning* an elongated S into a connected *skeleton* (e.g., [114]). The skeleton can be decomposed into branches that correspond to protrusions of S [20].

S is called *convex* [240] if any line segment joining two pixels of S lies entirely in S ; any such S must be simply connected. The smallest convex set \hat{S} containing S is called the *convex hull* of S , and the connected components of $\hat{S} - S$ are called the *concavities* of S .

Image parts are often difficult to define precisely; it may be advantageous to regard them as fuzzy subsets of the image [278, 200]. Definitions of image part properties can often be generalized straightforwardly to fuzzy image parts [278, 24, 219].

4.3 Classification and description

An image or image part can be *classified* on the basis of the values of its properties. The process of classifying a pattern (e.g., an image) based on property values is studied in the field of pattern recognition. If the probability distribution of the values of the properties is known for each class, and the a priori probabilities of the classes are also known, Bayes' theorem can be used to compute the probability that a given pattern (having an observed set of property values) belongs to each class. This *statistical pattern recognition* paradigm is not specific to patterns derived from images; it will not be discussed further here.

An image can be *described* as consisting of parts that have given properties and that are related to one another in various ways; this is the *structural pattern recognition* paradigm [192]. Relationships that may be of interest for descriptive purposes include relative values of properties (darker than, larger than, ...); set-theoretic and topological relationships (contained in, intersecting, adjacent to, surrounded by, ...); and relationships of relative position (near/far, above/below/right/left, between; on an early attempt to define such relationships see [268]). A structural description of an image in terms of parts, properties, and relations can be represented by a labeled graph in which the nodes correspond to the parts; each node is labelled with its property values; and the arcs represent relations between the parts, labeled with their values. For an early discussion of such relational descriptions see [12].

Describing an image as a configuration of parts, which may in turn be composed of

subparts, etc., is analogous to “parsing” a sentence into clauses, phrases, etc. [171]. This idea led to a number of attempts to define *picture grammars* that could be used to parse (or generate) classes of pictorial patterns, or (labelled) *graph grammars* for classes of relational descriptions. For some early examples of such approaches see [140, 181, 182, 170, 54, 37, 36, 183, 235, 196]. There were many additional papers on this subject in the 1970’s; we mention here only a few major examples of work related to this area [79, 87, 88, 89]. An early conference on the subject was [289]; a book on the subject is [221]. (The still ongoing series of International Workshops on Graph Grammars began in 1978 [35]; for a book on the subject see [179].) Picture languages can also be characterized as the classes of pictures that are accepted by various types of two-dimensional automata (e.g., see [136]). These concepts led to extensive work on *syntactic pattern recognition* starting in the 1970’s; basic references on this subject are [71, 72, 73, 82] (see also [194]).

Many other image analysis techniques were studied during the 1960’s and 70’s; the author’s first ten bibliographies on image processing and analysis [209, 212, 214] contain nearly 5000 references. This review is restricted to highlights and milestones; it does not claim to be comprehensive.

5 Computer vision: scene analysis

In several of the areas of application of image analysis described in Section 3, the “objects” that appear in the images are essentially two-dimensional; this is obvious in the case of character recognition, where the objects are marks on a flat paper surface, and it is also true in microscopy, where because of the extremely shallow depth of field of a microscope, the image shows a flat “slice” (an “optical section”) of the object. In other areas, the objects are three-dimensional, but they are viewed from a known direction, so that the images show known projections of the objects; this is the case in conventional radiology and in downward-looking remote sensor imagery. [In the remote sensing case, the images are also taken from a great distance, so terrain relief can sometimes be regarded as negligible.] These considerations allow us to regard a two-dimensional image as an adequate representation of the scene containing the objects, and to analyze the scene using the image analysis paradigm of Figure 3.

When a scene is imaged from an unknown viewpoint which is not very distant relative to the sizes of the objects in the scene, the image can no longer be regarded as an adequate representation of the scene, since it no longer shows a known projection of the objects, and objects may also (partially) occlude one another. In such situations, the paradigm of Figure 3 is evidently inadequate. This became apparent when the artificial intelligence laboratories at such institutions as MIT, Stanford, and SRI were established and began to work on problems of robot vision; a robot must manipulate, or navigate among, objects that are close to it and lie in arbitrary directions relative to it.

Today’s computer vision systems deal with sequences of images of dynamic scenes, containing moving objects and obtained by moving cameras. The images may be obtained by multiple cameras (allowing scene depth to be determined by measuring the positions of the images of a scene point in images obtained by different cameras), or may be obtained by range sensors that allow the depths of scene points to be measured directly); but for the mo-

ment we shall continue to consider only single, conventional images. Even in this restricted situation, a more complex paradigm is needed to describe the process of inferring a description of a three-dimensional scene from an image. Such a paradigm is shown schematically in Figure 4.

The scene analysis paradigm of Figure 4 differs from the image analysis paradigm of Figure 3 in two principal ways:

- a) It incorporates processes that *recover* information about relative depth from the image, or from sets of local features detected in the image. If simple assumptions about illumination and surface reflectivity are satisfied, the orientation of a homogeneous surface can be inferred from gray level variations across its image ("shape from shading"). Similarly, the orientation of a homogeneously textured surface can be inferred from variations in the spacings of local features in its image ("shape from texture"). The occlusion of one surface by another can be inferred from the shapes of the junctions at which region boundaries meet ("shape from contour"); for example, the presence of a T-junction suggests that the surface giving rise to the region above the horizontal line of the T is in front of the surfaces giving rise to the regions below it, because the boundary between the latter two regions (the leg of the T) appears to be occluded. Note that this "recovered" information is viewpoint-dependent—i.e., it describes depth relative to the observer (the camera). Such information is called *2-1/2-dimensional* because it relates only to the parts of the scene that are visible to the observer, and not to the hidden parts of the scene (occluded objects; backs of objects).
- b) If 2-1/2-dimensional information is available, the image can be segmented into regions that correspond to connected visible surface patches in the scene. The shapes of these image regions are strongly dependent on viewpoint, because of both occlusion and perspective distortion; thus the identities of the objects that appear in the scene, and their spatial layout, cannot be directly derived from the properties of and relationships among the image regions. However, if the set of possible objects is limited (and known), it is possible in principle to determine which of these objects, seen from which viewpoint, could have given rise to the observed set of image regions; this "back-projection" process allows us to infer the identities and "poses" of the visible objects, as well as the layout of these objects in the scene.

Early research on three-dimensional scene analysis dealt with scenes containing simple geometrical objects (the "blocks world"). The first Ph.D. dissertation on this subject, at the MIT Artificial Intelligence Laboratory, was that of Roberts (see [206].) (For early papers on robot vision at MIT, Stanford, Edinburgh, and SRI see [166, 61, 197, 57, 269, 11, 53].) The knowledge that a scene consists of polyhedral objects can be used as a guide in segmenting images of the scene [90, 236, 237]. In the mid-60's an attempt was made at MIT to develop a system that could recognize many different common objects (hand tools) [190], but this effort was not successful.

Research on recovery techniques was also initiated in the 1960's. The first Ph.D. dissertation on shape from shading, also at MIT, was that of Horn in 1970 (see [117]; for his later work on the subject see [118]). The concept of shape from texture was introduced

in a 1950 book on visual perception by Gibson [77]; early attempts at implementing this concept were not entirely successful [25], but better results were achieved in the 1970's [8]. The first Ph.D. dissertation on shape from contour, developing rules for identifying regions that (probably) belong to different polyhedral objects, was that of Guzman at MIT [94]; a theoretical basis for Guzman's rules was developed in the early 1970's by Huffman [126] and by Clowes [38] (see also [155]), and was extended by Waltz to allow for contours due to cracks or shadows [258]. Guzman also formulated rules about contours of curvilinear objects [95]; for systematic treatments of such rules see [28, 244]. Another approach to shape from contour, involving the inference of surface orientation from contour shape (or spacing, as in shape from texture) was investigated by Stevens [244]. A general treatment of recovery techniques is given in [13].

During the 1970's, Marr at MIT formulated a paradigm for visual information representation that involved 2D feature analysis (the "primal sketch"), relative depth recovery (the "2-1/2-D sketch"), and object recognition using 3D object models [159, 160, 161]. For collections of 1970's MIT papers on scene analysis see [270, 272]. Another approach to model-based object recognition is described in [23]; a system for analyzing images of natural scenes is described in [102].

Quantitative depth information about a scene can be obtained by stereo triangulation or by direct range sensing. Early work on automation of stereomapping is reviewed in [50]; for robot vision purposes, more powerful methods were needed to achieve short-range stereopsis [99]. Important models for human stereopsis also appeared during the 1970's (e.g., [132, 162]), and "photometric stereo", in which surface orientation information is derived by comparing the shading in two or more images taken from the same camera position under different illuminations, was introduced in 1979 [275]. Patterned illumination became widely used for range imaging (e.g., [266, 267]). An early study of range image analysis was [186]; applications to the description and recognition of objects composed of "generalized cylinders" are described in [4, 185]. The first meeting on representation of three-dimensional objects was held in 1979 [308].

The first Ph.D. dissertation on visual motion analysis based on feature point correspondences was that of Ullman at MIT in 1977 [251]. A 1979 book on visual perception by Gibson [78] (see also his 1950 book [77]) emphasized the importance of "optical flow" in a moving observer's perception of its environment. An early example of dynamic scene analysis using optical flow is [56]; on motion-based image segmentation see [128], [129]. Koenderink and Van Doorn extensively studied the structure of the parallax field generated by motion relative to a solid body (e.g., [144, 145]). Two surveys of early work on image sequence analysis appeared in 1978 [165, 178], and the first workshop on the analysis of time-varying imagery was held in 1979 [2].

6 Milestones

Early papers on image analysis appeared in general electrical engineering or computing conferences. By the 1960's, specialized paper collections and workshop proceedings on pattern recognition began to appear [134, 259, 283, 284, 138, 70, 260, 293, 49, 295, 29, 32], leading to the initiation of the International Conferences on Pattern Recognition in the early 1970's;

most of the papers at these conferences continue to deal with image analysis. Papers on both image and scene analysis also appeared in the Machine Intelligence Workshops, initiated in the mid-1960's, and the International Joint Conferences on Artificial Intelligence, initiated at the end of the 1960's.

Conferences on image processing and analysis also began to be held in the 1960's [281, 137, 39, 31, 158, 86, 153, 287, 187, 288, 26, 290, 291, 168, 294, 143, 254, 52, 239, 296, 265, 177, 100, 303, 151, 305, 105, 76, 243, 250, 60]. A series of workshops on Automatic Imagery Pattern Recognition (initially: Automatic Photointerpretation and Recognition), initiated in 1970, is still ongoing. The annual IEEE Conferences on Pattern Recognition and Image Processing (later retitled Computer Vision and Pattern Recognition) were initiated in 1977, as were the annual SPIE Conferences on Applications of Digital Image Processing and the DARPA Image Understanding Workshops (initially semiannual, later annual and sesquennial).

The first two of an ongoing series of bibliographies on image processing and analysis appeared in 1969 and 1973 [209, 212]; they have appeared annually since then [214], and now deal only with image analysis and computer vision. A late 1970's survey paper is [220].

The first book on image processing and analysis appeared in 1969 [210]; a book on pattern recognition and scene analysis appeared in 1973 [48]. Other books published in the 1970's dealt, at least in part, with image or scene analysis [252, 226, 83, 192, 271, 16, 198, 27, 96, 272]; a collection of important reprints is [3]. During the 1970's the major electrical engineering and computing journals published special issues devoted to image analysis [106, 97, 74].

The first journal on pattern recognition was started in 1968 [150]; the first journal on artificial intelligence, in 1970 [167]; and the first journal on computer graphics and image processing (including image analysis), in 1972 [67]. The first IEEE journal in the field, the Transactions on Pattern Analysis and Machine Intelligence, was started in 1979; many other journals were started during the 1980's and 90's. [A graphics journal was started in 1975, but the IEEE Computer Graphics and Applications Magazine was not started until 1981, and the ACM Transactions on Graphics began publication only in 1982. Papers on image processing appeared in signal processing journals for many years; the IEEE Transactions on Image Processing was not started until 1992.]

A conference devoted to OCR was held in 1962 [58], and a Postal Service conference was held in 1969 [135]; work in the USSR is described in [146]. Conferences on industrial automation applications did not begin until the 1970's [255, 257, 184, 46, 148, 34]. Early conferences on biomedical image analysis dealt primarily with microscope images [204, 249, 51, 263, 130, 238, 302, 75, 309], but by the 1970's, work on radiographs was also being reported [98, 111, 112, 199, 298, 306]. Later publications also dealt with electron microscopy [107, 108, 232], and there were also specialized conferences on topics such as cytogenetics [299, 85]. There were Engineering Foundation Conferences on Automatic Cytology throughout the 1970's, and a journal on automated cytology was started in 1979 [262].

An early collection of papers on remote sensing is [154]; an early automatic target recognition system is described in [116, 115]. A series of conferences on Machine Processing of Remotely Sensed Data was initiated in 1973 [292]. Other conferences on the subject were [297, 149, 304, 307, 264]; on image processing in astronomy see [44], and on target recogni-

tion see [69, 241, 9]. A collection of important reprints on the subject is [17], and a book is [245]. An early conference on forensic applications was [277]. For early work on face recognition see [139, 81, 133]. Some early conferences on high-energy physics applications are [282, 231, 285, 286, 41]. A mid-1970's book [217] consisted of review articles on the major application areas.

Computer architectures appropriate for image processing and analysis have been an issue of interest since the 1950's [253]. A workshop on the subject was held in the late 1970's [189], and by the 1980's, regular conferences on the subject were being held. Another topic which began to receive attention in the 1970's, and is now of major interest, is that of image (and video) databases [301, 18].

7 Concluding remarks

Research on image analysis and computer vision over the past 40 years has led to the formulation of many elegant mathematical models and algorithms. Unfortunately, most vision problems, even those that were first tackled in the 1950's, are mathematically ill-defined (reading handwritten words, counting cells, recognizing buildings). Real-world visual domains do not satisfy simple mathematical (even probabilistic) models. Even if adequate scene models could be formulated, problems that involve inferring information about a scene from images are often mathematically ill-posed or computationally intractable; but the primary reason why vision is hard for computers is that the scene models used (often tacitly) in today's computer vision systems are unrealistic, and this situation is likely to persist for a long time to come.

The inadequacy of our scene models does not imply that computer vision systems will never perform adequately. Animals (and humans) use vision quite effectively in the real world. A possible basis for this is that biological visual systems make use of redundant visual data and process it redundant ways. Computer vision systems usually avoid such redundancy in order to reduce computational cost. But redundancy may allow the biological systems to detect processing errors, since they are likely to give results that are inconsistent or non-persistent.

Computer vision systems are just reaching the levels of processing power that will allow them to handle, in real time, amounts of input data comparable to those handled by biological visual systems, and to apply multiple processing techniques to the data. The techniques used nowadays in these systems are often quite simple, even "brute force"; but more complex algorithms, which today can only be demonstrated in the laboratory, will run at video rates on tomorrow's processors. As processing power continues to increase, some of these algorithms will be applied to real-world problems; as a result, the performance of computer vision systems will gradually improve.

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		OUTPUT	
		Image	Descriptive data
I N P U T	Image	Image Processing	Pattern Recognition (image description)
	Descriptive data	Computer Graphics (image synthesis)	(Non-image-related uses of computers)

Figure 1: An “imagecentric” view of data processing: The relationship between image processing, pattern recognition, and computer graphics.

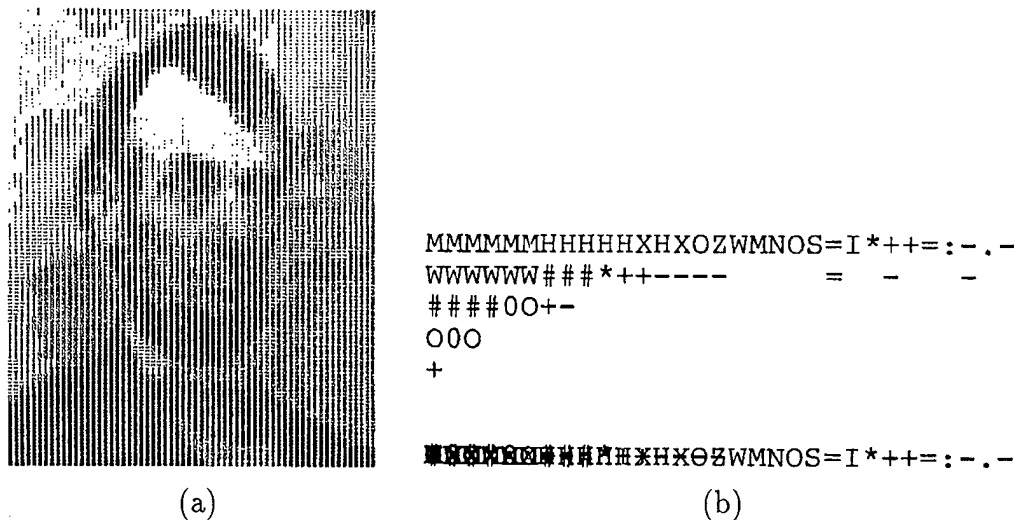


Figure 2: (a) An example of the use of overstrike on an alphanumeric printer to generate “halftone” images. (b) The sets of overstruck characters used to produce (a). [From R.C. Gonzalez and P.A. Wintz, *Digital Image Processing*, Addison-Wesley, Reading, MA, 1977.]

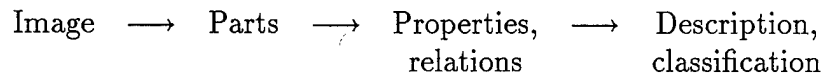


Figure 3: A general image analysis paradigm.

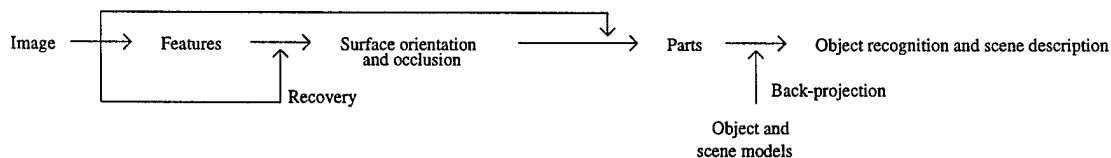


Figure 4: A general scene analysis paradigm (for a single static image).

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13. ABSTRACT (Maximum 200 words) Almost as soon as digital computers became available, it was realized that they could be used to process and extract information from digitized images. Initially, work on digital <i>image analysis</i> dealt with specific classes of images such as text, photomicrographs, nuclear particle tracks, and aerial photographs; but by the 1960's, general algorithms and paradigms for image analysis began to be formulated. When the artificial intelligence community began to work on robot vision, these paradigms were extended to include recovery of three-dimensional information, at first from single images of a scene, but eventually from image sequences obtained by a moving camera; at this stage, image analysis had become <i>scene analysis</i> or <i>computer vision</i> . This paper reviews research on digital image and scene analysis through the 1970's. This research has led to the formulation of many elegant mathematical models and algorithms; but practical progress has largely been due to enormous increases in computer power, allowing even "brute force" algorithms to be implemented very rapidly.				
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